Scintillators with Silicon Photomultiplier Readout for Timing Measurements in Hadronic Showers

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Abstract—The advent of silicon photomultipliers has enabled big advances in high energy physics instrumentation, for example by allowing the construction of extremely granular hadronic calorimeters with photon sensors integrated into small scintillator tiles. Direct coupling of the SiPM to the plastic scintillator, without use of wavelength shifting fibers, provides a fast detector response, making such devices well suited for precise timing measurements. We have constructed a setup consisting of 15 such scintillator tiles read out with fast digitizers with deep buffers to measure the time structure of signals in hadronic calorimeters. Specialized data reconstruction algorithms that allow the determination of the arrival time of individual photons by a detailed analysis of the recorded waveforms and that provide automatic calibration of the gain of the photon sensor, have been developed. We will discuss the experimental apparatus and the data analysis. In addition, we will report on first results obtained in a hadronic calorimeter with tungsten absorbers, providing important constraints on the time development of hadronic showers for the development of simulation models.

Index Terms—Silicon Photomultiplier, Scintillator, Calorimetry, Timing

I. INTRODUCTION

Multi-cell Geiger-mode avalanche photodiodes (G-APDs), often referred to as Silicon Photomultipiers (SiPMs) [1] have a wide range of applications in high energy physics instrumentation. They provide high photon detection efficiency and insensitivity to magnetic fields with very compact devices. A large number of such devices, approximately 8 000, have been successfully used to read out small plastic scintillator tiles in the CALICE analog hadron calorimeter [2], a physics prototype of a highly granular calorimeter for detectors at the future International Linear Collider (ILC). In addition to the proof of technology, the test beam campaigns with this and other calorimeter prototypes also yield information on the structure of hadronic showers with unprecedented precision, providing important input for the further development of hadronic shower models used in simulation tools for high energy physics and beyond.

The development of detector concepts for the Compact Linear Collider (CLIC) [3] has led to considerable interest in using tungsten instead of steel absorbers also in the hadronic calorimeters, since this allows compact detectors. At CLIC, time stamping of signals will be of key importance, requiring the study of the intrinsic time structure of hadronic showers in a tungsten calorimeter with scintillator readout, to evaluate the impact of physical processes on the achievable time resolution.

II. EXPERIMENTAL SETUP

To provide first measurements of the time structure of hadronic showers in a tungsten calorimeter with scintillator
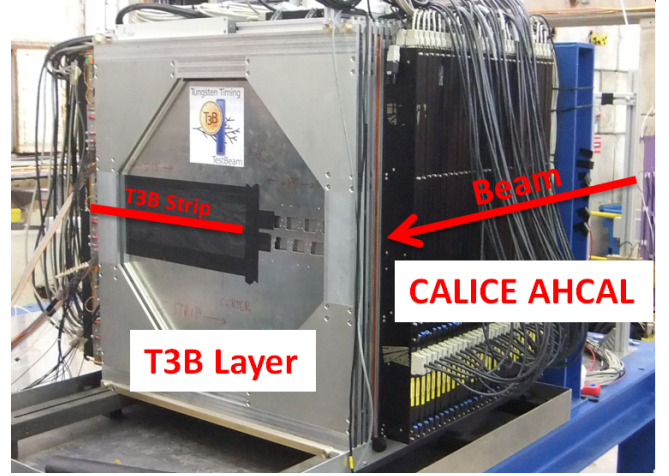

Fig. 1. The CALICE analog tungsten HCAL at the CERN PS, with the T3B setup installed in the last layer of the detector.
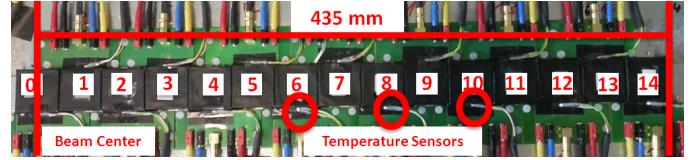

Fig. 2. Layout of the 15 T3B scintillator tiles, covering the radial shower profile from the beam line to the outer region. Each tile is equipped with a sensor which monitors temperature variations close to the SiPM coupling position.

readout, a dedicated apparatus, the T3B (Tungsten Timing Test Beam) experiment, has been constructed. This device is operated together with the main CALICE analog scintillator tungsten HCAL, as an additional active layer behind the main detector. The setup consists of 15 scintillator cells with a size of 3×3 cm^2 and a thickness of 5 mm, with directly coupled photon sensors. As direct coupling requires the sensitivity maximum of the sensors to match the light emission maximum of conventional scintillators, blue sensitive SiPMs developed by Hamamatsu[1] were used. Without wavelength-shifting fibers, these cells provide a fast response to ionizing particles. A uniform response across the whole surface area is provided by a special shaping of the coupling position, as discussed in [4]. The 15 T3B cells are arranged in one row extending from the center of the calorimeter out to one side of the detector (Figure 1) and positioned in a depth of 4 nuclear interaction lengths. The analog SiPM signals are read out with four 4-channel USB-oscilloscopes[2] which
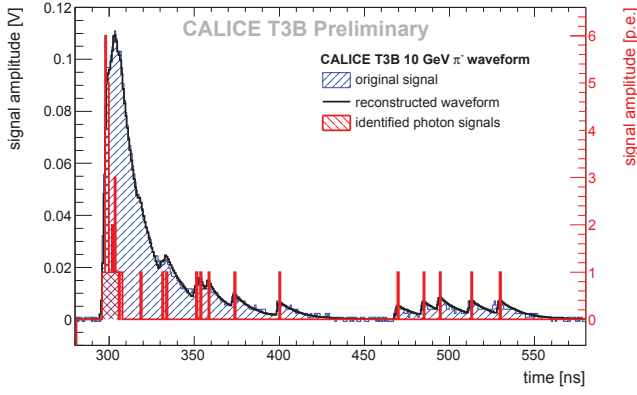
Fig. 3. Typical waveform of a T3B shower event on one channel. The original SiPM signal (blue) is iteratively decomposed into its single photon contributions using the averaged 1 photon signal from calibration data. The obtained time distribution of single photon hits (red) can be used to reconstruct the original waveform (black) and validate the success of the procedure.
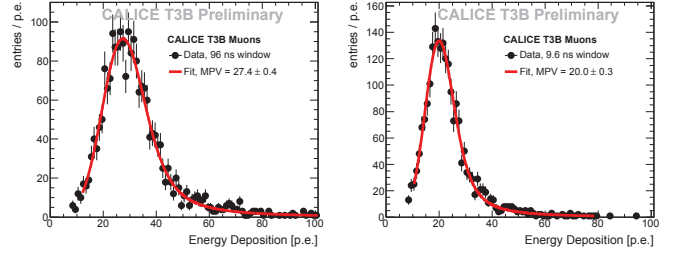

Fig. 4. Measured spectrum for muons in the central T3B scintillator tile, reconstructed by identifying the time of individual photon signals in the SiPM, for two different integration time windows: 96 ns from the first identified photon (left) and a time window of 9.6 ns (right). The distributions were fitted with a Landau function convolved with a Gaussian to extract the most probable value. In both cases, the χ^2 per degree of freedom is around 0.8, indicating a good fit quality.

provide a sampling rate of 1.25 GSa/s on all channels and are therefore well suited for precise timing measurements in the nanosecond region. Long acquisition windows of $2.4\mu s$ per event are recorded to study the time structure of the energy deposits in the scintillator in detail, providing information on the time structure of hadronic showers in the calorimeter.

Shower events are triggered synchronous with the CALICE HCAL to allow for an event correlation of T3B to CALICE data. In the main calorimeter, the position of the first inelastic hadronic interaction can be determined event by event, allowing to measure the time structure of the shower at various depths with respect to the shower start, which can be used to measure the averaged timing profile over the full longitudinal and lateral extent of the shower.

The T3B detector was part of the CALICE test beam campaign at the CERN Proton Synchrotron in 2010 and at the Super Proton Synchrotron in 2011, and successfully acquired large data sets of hadronic showers in an energy range of 2-300 GeV.

III. DATA RECONSTRUCTION

The intrinsic properties of SiPMs require a dedicated set of calibration tools. A specialized data reconstruction algorithm was developed to determine the arrival time of individual photons at the sensor with sub-nanosecond precision eliminating any influence of the temperature dependence of the SiPM gain at the same time.

At test beam facilities, a certain number of particles is delivered to the physics experiments within a time window of a few seconds (for the SPS) in so-called spills, leaving the experiments time for readout and calibration before the next particle spill arrives. The T3B detector recorded physics events during the spill and SiPM dark count events in between spills for live calibration purposes of the corresponding physics events.

As a first step in the calibration sequence, zero suppression based on pedestals determined on a spill-by-spill basis was applied to the aquired SiPM signals.

Then, the signals were decomposed into individual photon equivalents. Selecting single pixel dark count waveforms from the inter-spill calibration data and averaging the waveforms on a cell-by-cell basis over 10 spills corresponding to less than 5 minutes, one obtains a reference signal for a single SiPM geiger discharge or a single detected photon respectively. This averaged calibration waveform is then iteratively subtracted from local maxima detected in the corresponding physics waveforms until no maxima above 0.5 p.e. remain. Figure 3 shows one example of a waveform decomposed using this reconstruction technique. To check the quality of this analysis, a waveform based on the identified photon signals was built up with the reference single photon signals and compared to the original waveform. The very good agreement between measurement and the reconstructed waveform demonstrates the quality of reconstruction.

The calibration procedure results in an implicit gain calibration, since possible cell-to-cell gain differences lead to corresponding differences in the average single photon signals used in the calibration. The resulting number of photons is thus independent of the SiPM gain. Due to the continuous automatic updating of the average single photon waveforms, the T3B detector is not affected by SiPM gain variations due to temperature changes and the temperature dependence of the measured signal amplitudes is significantly reduced. Additionally, the calibration procedure results in a data reduction factor of approximately 1000. Any further data analysis was executed on waveform decomposed T3B events using the timing of each identified photon.

Figure 4 shows the distribution of the energy reconstructed with this technique in the central tile of the T3B detector for muons obtained in a special data run with an absorber in the beam line. The deposited energy was determined with two different integration windows, 96 ns from the first identified photons, shown in Figure 4 *left* and 9.6 ns, shown in Figure 4 *right*. The most probable value of both distributions was extracted by fitting a Landau function convoluted with a Gaussian. The integration time has a considerable effect on the most probable value, which is reduced by almost 30% from 27.4 ± 0.4 p.e. to 20.0 ± 0.3 p.e. for the reduced integration window. Also the width of the signal is reduced considerably.
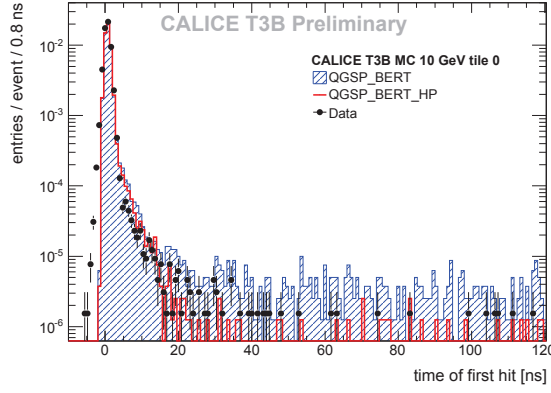
Fig. 5. Comparison of the time of first hit distribution in the central T3B tile simulated for 10 GeV π^- with QGSP_BERT (blue) and QGSP_BERT_HP (red) with data (black).

Fig. 6. Mean time of first hit for 10 GeV π^- as a function of radial distance from the shower core (a tile index of 10 corresponds to approximately 30 cm). The data are compared with simulations using QGSP_BERT and QGSP_BERT_HP. The error bars and the width of the area in the case of QGSP_BERT_HP simulations show the statistical error, while for QGSP_BERT the errors are omitted for clarity.

This is due to the partial exclusion of contributions from afterpulses of the photon sensor.

Further calibration algorithms are to be applied to address thermal darkrate and signal afterpulsing and to calibrate energy depositions to the scale of minimum ionizing particles.

IV. FIRST RESULTS

As a first parameter in the investigation of the time structure of hadronic showers, the time of the first energy deposit is studied. This parameter provides a good indication of the intrinsic time stamping possibilities in the calorimeter. The analysis is performed on the decomposed waveforms for a 10 GeV π^- run with 718 000 events. A SiPM signal is considered as energy deposition where at least 8 photon equivalents are detected within 12 time bins (9.6 ns). The time of hit is then taken from the timing of the second detected photon of that deposition. It was observed that using the first instead of the second photon leads to additional jitter due to single p.e. dark counts before the starting time of the real hit. The distribution of the time of first hit for the central T3B tile is shown in Figure 5. A simulation study, based on a direct implementation of the CALICE tungsten HCAL geometry together with an approximation of the T3B detector in GEANT4 [5] was performed to provide first comparisons to the T3B results. The data was compared to two different hadronic shower models, QGSP_BERT, and QGSP_BERT_HP [6], a variant which provides additional high precision neutron tracking, and is expected to give an improved description of the shower evolution in heavy absorbers, while the former is the physics list mostly used in the simulation of LHC detectors and for linear collider optimization studies. Figure 5 illustrates a striking difference in the late shower evolution for the two GEANT4 physics models. The delayed energy deposits are considerably reduced in the model including high precision neutron tracking and this model is consistent with the observation in data. This is most prominent in the tail of the hit distribution beyond 20 ns. The main peak is reasonably well described by both models. The standard QGSP_BERT list on the other hand overestimates isolated late energy depositions, where isolated means that only the time of the first hit is taken
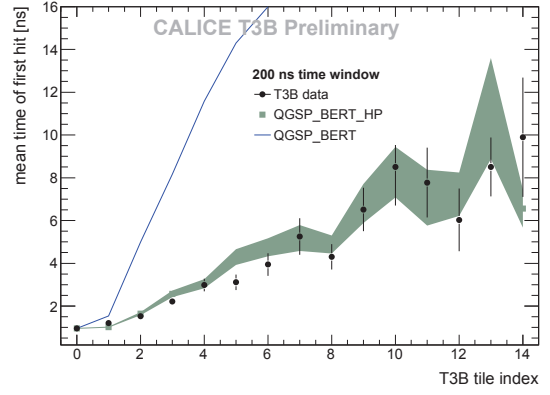
into account in case of multiple hits on one tile in the same event.

To provide first information on the lateral shape of the time development of hadronic showers, the mean time of first hit for each of the T3B cells was determined from the distribution of the first hit discussed above. The mean was formed within a time window of 200 ns, starting 10 ns before the maximum of the distribution in T3B tile 0. This time window covers the time relevant for calorimetry at CLIC, where the duration for one bunch train is expected to be 156 ns. Figure 6 shows the mean time of first hit as a function of the radial distance from the shower axis. The beam axis passes through T3B tile 0, so that a tile index of 10 corresponds to a distance of approximately 30 cm. While QGSP_BERT_HP gives an excellent description of the data, QGSP_BERT shows very large discrepancies, with significantly overestimated late contributions at larger radii.

This demonstrates the importance of the high precision neutron tracking in GEANT4 for a realistic reproduction of the time evolution of hadronic showers in tungsten. Upcoming T3B results will investigate the time development of hadronic showers in detail and provide more information that can be used for the validation and further development of the timing aspect of shower models in GEANT4.

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